LANDING APPROACH HANDLING QUALITIES OF TRANSPORT AIRCRAFT WITH RELAXED STATIC STABILITY

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Abstract

Future transport aircraft will probably have relaxed static stability or static instability in order to increase aircraft performance. To investigate flying qualities problems associated with the relaxation of natural longitudinal static stability a flight test program was performed by DFVLR utilizing the HFB 320 in-flight simulator.

The main objective of this research program was to investigate the influence of c.g. position on landing approach flying qualities. The static margin was varied from 14 % MAC to -10 % MAC by rearward translation of the c.g. In addition the influence of pitch damping and pitch control effectiveness on the flying qualities of an unstable aircraft configuration was studied.

Nine configurations were evaluated by four pilots, who flew a total of 181 landing approaches under different natural atmospheric conditions.

Cooper-Harper pilot ratings and special effort ratings, as well as statistical values computed from measured performance data of the pilot aircraft system, are presented as a function of the parameters varied and the turbulence intensity.

1. Introduction

Conventional transport aircraft are designed so as to have good controllability in all degrees of freedom and adequate natural stability in all modes of motion. In order to increase aircraft performance it is expected that future aircraft will probably have relaxed static stability or static instability. A relaxation of natural longitudinal static stability, however, can lead to flying qualities problems since the pilots are required to pay closer attention to pitch control and airspeed control.

To avoid problems associated with such a degradation in flying qualities, aircraft with relaxed static stability (RSS) in the Normal State will be flown either fully automatically or manually with a stability augmentation system (SAS) providing the stability which the aircraft inherently lacks.

In the event of a failure in the Flight Augmentation Computer (FAC) affecting the components of the stability augmentation system and in particular in the case of a total failure of the FAC, the aircraft must at least have minimum (level 3) flying qualities which ensure that the pilot can safely fulfill his mission.

2. Purpose of the Flight Test Program

The objectives of this in-flight research program, which utilized the DFVLR HFB 320 in-flight simulator, were

- to investigate the effect of the relaxation of longitudinal static stability on the landing approach flying qualities by moving the center of gravity to the rear, and
- to study the influence of pitch damping and pitch control effectiveness on the landing approach flying qualities for aircraft with static instability.

3. Experiment Design

3.1 Aircraft Model and Configuration Description

A large transport type aircraft was selected as a reference configuration. To investigate the *influence of stability reduction caused by c.g. translation* five configurations with c.g. position varying from 35 % to 59 % MAC were chosen. The neutral point of the selected aircraft was located at 49 %, the maneuver point dependent on the c.g. position was located between 60.5 % and 61.5 % MAC.

The statically unstable configuration with c.g. position located at 55 % MAC was taken as the basic configuration for the investigation of the *influence of pitch damping and pitch control effectiveness on flying qualities*. The values under investigation of both parameters were half and double the reference value.

For the investigation the model aircraft was represented by linearized equations of motion in landing approach condition in the on-board computer. The constant physical characteristics of all configurations (reference condition, mass, weight etc.) are listed below (Table 1).

True Airspeed V = 64.0 m/s
Altitude H = 762 m
Flight Path Angle γ = -3^{o}
Gear Down

Wing Area	S =	260.0 m^2
Span	b =	44.8 m
MAC	$\bar{c}$ =	6.6 m
Mass	m =	100 000.0 kg

Moments of Inertia

I_x = 5 150 000 kgm^2
I_y = 11 190 000 kgm^2
I_z = 16 300 000 kgm^2
I_{xz} = - 426 000 kgm^2

Table 1 Constant Model Aircraft Characteristics

3.2 Dynamic Characteristics

Influence of C.G. Position

The primary consequence of moving the c.g. to the rear is a destabilisation leading to instability in the longitudinal motion if M_α becomes positive.

Figure 1 shows the influence of different c.g. positions on the roots of characteristic motion in the landing approach flight phase for the selected aircraft.

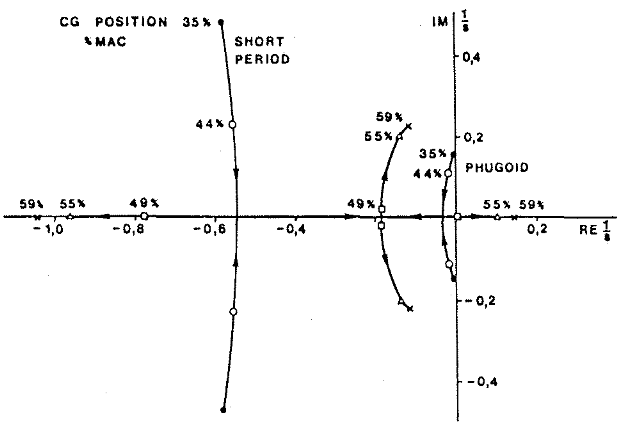

Figure 1. Influence of c.g. position on the roots of characteristic motion

Starting with the conventional short period and phugoid roots c.g. positions aft of the range which is normally used lead to frequency reductions of both eigenmotions until they change into aperiodic motions. As indicated in the root locus plot two real roots combine to form a new oscillatory mode for a further rearward shift in c.g. position.

For c.g. positions well behind the normally used c.g. range three poles are in the left half plane (stable), one of them being on the real axis and two of them characterizing an oscillatory mode, which behaves much like the phugoid mode. However, the fourth pole is located on the real axis in the right half plane. This positive root characterizes the unstable aperiodic response of such aircraft.

Relaxed static stability and static instability in particular affects the response of pitch attitude and speed. The level of instability is mostly measured in terms of the time-to-double amplitude of the aircraft's pitch response (T_2) calculated from the unstable root. Figure 2 shows the time-to-double amplitude of pitch attitude ($T_{2\theta}$) versus c.g. position.

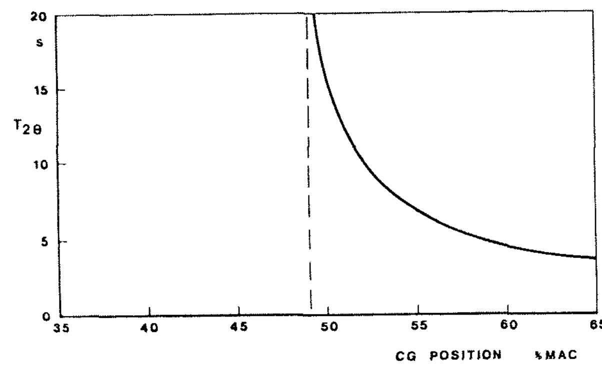

Figure 2. Time-to-double amplitude versus c.g. position

Influence of Pitch Damping and Pitch Control Effectiveness

To investigate the effect of pitch damping and pitch control effectiveness both parameters, the pitch damping coefficient C_{mq} and the pitch control effectiveness $C_{m\delta es}$ were varied. The values under investigation of both parameters were half and double the reference value.

The inherent instability of the reference configuration, characterized by the time-to-double amplitude T_2 = 6.8 sec., remained unchanged throughout the investigation. This was achieved by simultaneously changing the stability parameter $C_{m\alpha}$. In Table 2 dynamic characteristics are listed for all of the selected aircraft configurations (see Appendix 1).

4. Test Description

4.1 Evaluation Task

The piloting task was to execute landing approaches in normal ATC condition and during natural atmospheric disturbances of crosswinds, shear and turbulence. Radio communication was undertaken by the safety pilot but all information was also available to the evaluation pilot. The evaluation task consisted of the following:

precision tracking of the ILS beam, preceded by a glideslope intercept at an altitude of 2500 ft. Approach speed was defined to be 142 knots (landing gear extended). The evaluation pilot had to perform a level-off followed by a go-around at 500 ft GND and had to retract the landing gear.

The evaluation pilots were instructed to fly both glidepath and airspeed as accurately as possible. The ILS signals displayed on the evaluation pilot's instruments were changed by onboard computation in such a way that the pilot, in performing a level-off at 500 ft GND, obtained the information which he normally only receives from flare-out to touchdown.

4.2 Pilot Briefing and Comment

Four evaluation pilots participated in this flying qualities investigation. Each evaluation pilot was given a pre-evaluation flight of about two hours to become familiar with the reference model configuration. In this flight, the pilot carried out several approaches.

A total of 44 evaluation missions with 181 landing approaches were performed during the flight test program. The pilots received a written briefing guide and rating information. Before flying they were orally briefed on the general experiment purposes and simulation procedures. The evaluation pilots were given no information about the configuration flown. The complete mission consisted of five approaches.

During the flight pilot ratings and commentary were recorded on a tape recorder. After each approach the pilots were asked to assign "effort ratings" for a number of subtasks. A Cooper-Harper rating was given after the last approach of one mission for both longitudinal and lateral-directional dynamics. At the end of the evaluation flight, the pilot gave his formal commentary using a comment card.

4.3 Data Recording

A 120-channel digital recorder was used for onboard recording. All signals of interest were recorded at 10 samples per second. These included:

1. Tracking deviation
2. Pilot activity
3. Control surface motions
4. Aircraft states - model and HFB 320
5. Control system signals

In addition pilot ratings and comments were recorded on a separate voice recorder.

5. Experiment Mechanization

5.1 HFB 320 Aircraft

The DFVLR HFB 320 in-flight simulator was used as the test vehicle in this flight test program (Figure 3). The DFVLR HFB 320 is a five degrees of freedom simulator with a digital model-following control system. A detailed description of the HFB 320 is given in Reference[1].

Figure 4 shows the in-flight simulation equipment. Conventional controls (wheel, column and pedals) were used. The cockpit instruments for the evaluation pilot are shown in Figure 5. The primary instruments on the panel were standard instruments.

Figure 3. DFVLR HFB 320 In-Flight Simulator

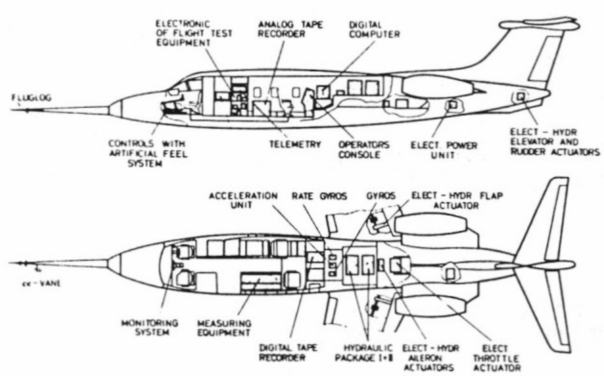

Figure 4. In-Flight Simulator equipment

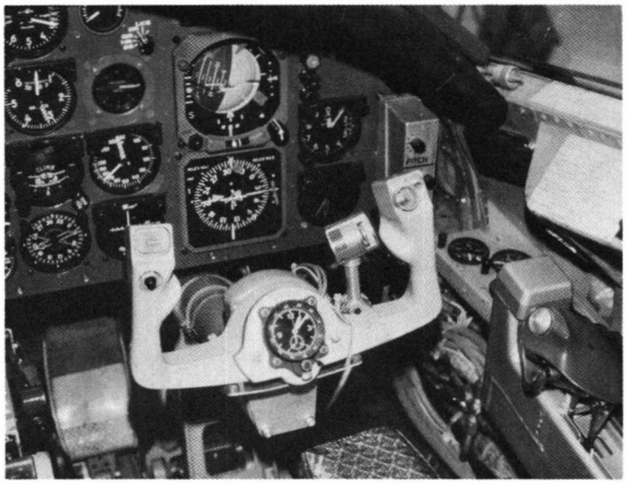

Figure 5. Evaluation pilot's cockpit instrumentation

5.2 Simulation Verification

The verification of the model-following control system was done on the ground, using a complete aircraft-system real-time simulation, and also in flight. The simulation accuracy demonstration in flight was made by using step and doublet inputs and by comparing model and actual aircraft responses. Samples of model-following responses are shown for configuration A4 (c.g. position of 55 % MAC) in Figure 6. In this figure the dashed lines show the time histories of selected parameters of the model, the continuous lines show the time histories of the respective parameters of the in-flight simulator. The HFB 320 motion system was configured to reproduce the motion of the model at the pilot's seat.

6. Experiment Results and Analysis

6.1 Introduction

In this section the main results of the flight test program are presented. More detailed information is given in References [2,3].

The data obtained from the experiment are in the following form:

1. pilot Cooper-Harper ratings (longitudinal and lateral)
2. pilot effort ratings using the pilot questionnaire for
   - a number of subtasks
   - the total task
3. pilot commentaries using the pilot comment card
4. on-board recorded data of tracking deviations, pilot activity, control surface deflections, model and aircraft state variables.

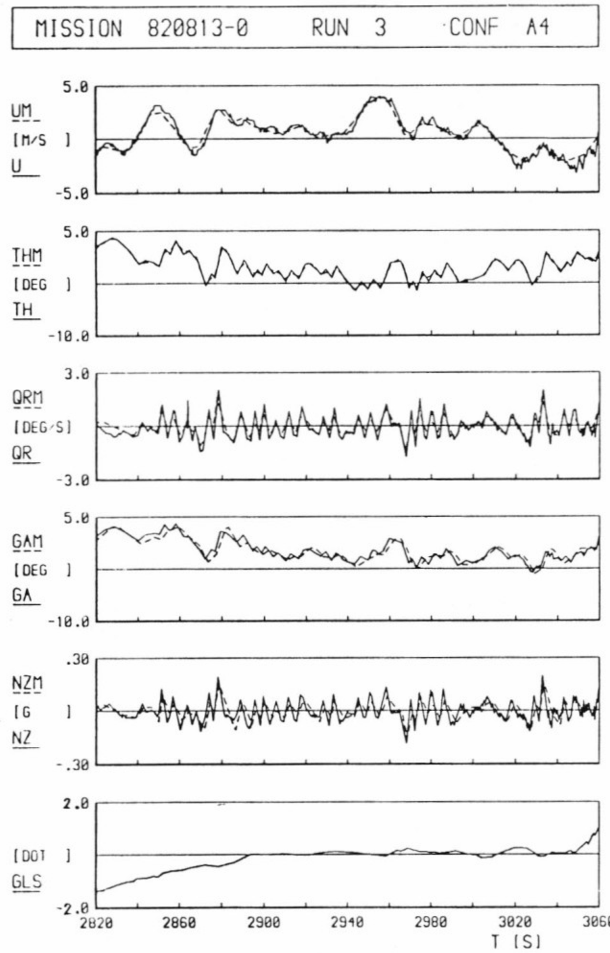

Figure 6. Sample of model-following responses

The pilots were instructed to characterize the turbulence intensity encountered during the landing approaches by classifying turbulence at one of three levels of intensity: smooth/light/moderate. In a later stage of the evaluation the standard deviation of vertical gust intensity was calculated from on-board measured values and correlated with pilot comments on the turbulence levels.

The calculated values together with pilot comments were used to determine the following boundaries of turbulence intensity:

light:	$\sigma_{wg} < 1$ m/s
moderate:	$1 \text{ m/s} \le \sigma_{wg} \le 1.75$ m/s
severe:	$\sigma_{wg} > 1.75$ m/s

In the following figures, open symbols indicate light turbulence intensity whereas moderate turbulence intensity is indicated by full symbols.

Each landing approach was documented by time history plots. For each mission (five approaches) statistical data (mean value, standard deviation) were computed from different variables of approach.

6.2 Results

Influence of C.G. Position

In Figure 7 the influence of c.g position translation on Cooper-Harper ratings is presented for all missions investigated in this part of the flight test program. In addition turbulence intensity, as characterized by the boundaries given in the previous paragraph, is indicated. In this figure no clear tendency can be detected until the time-to-double amplitude reaches 6.8 seconds. All ratings are within a specific band of ratings; moreover turbulence seems not to be a major factor. It is remarkable only that in a great number of approaches pilots rated Configuration A2 the best of all configurations.

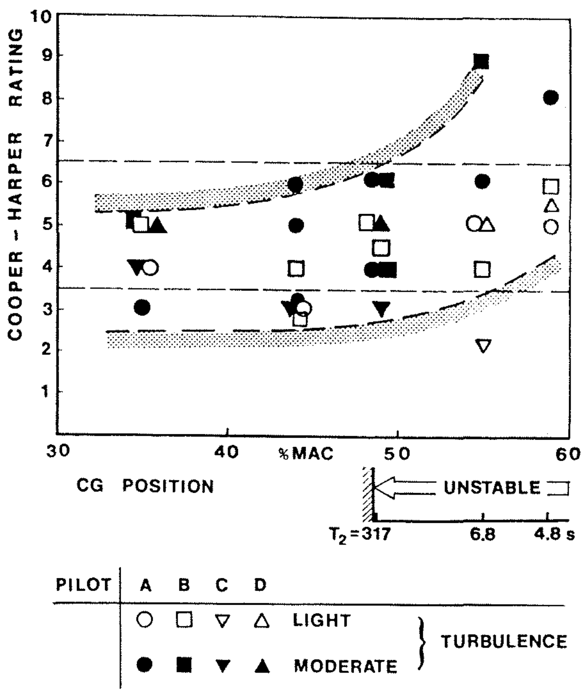

Figure 7. Cooper-Harper pilot ratings versus c.g. position

A deterioration in flying qualities, however, can be detected for configurations with a time-to-double amplitude of less than about 6 seconds (c.g. position 55 % MAC). In these cases pilot ratings are clearly influenced by turbulence intensity. This is shown in Figure 8, which presents for each configuration both the mean values of the Cooper-Harper ratings of all pilots and the corresponding bands of pilot ratings. From this figure an improvement in Cooper-Harper ratings from Configuration A1 to Configuration A2 can be identified. This confirms the tendency mentioned above that Configuration A2, with a c.g. position of 44 % MAC, was rated best in comparison with all other configurations. A further translation of the c.g. position to the rear, however, leads to an almost constant deterioration in mean pilot ratings. The gradient of the deterioration depends on the turbulence intensity.

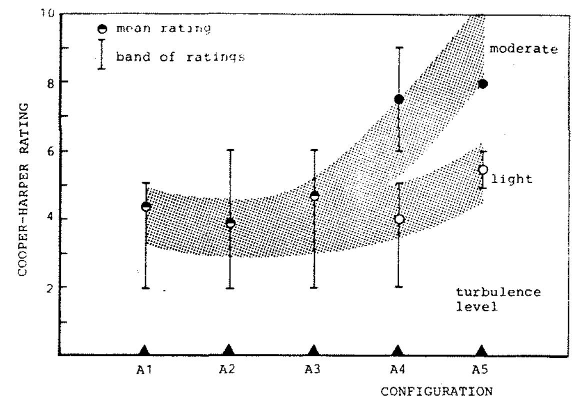

Figure 8. Cooper-Harper pilot ratings

To characterize the achieved performance of the pilot-aircraft system, measured performance data (mean value and standard deviation) of glideslope and airspeed are plotted in Figure 9 and Figure 10 for each pilot. As can be seen from both figures the deviations lie mostly within a band of ± 0.5 DOT in glideslope and ± 3 m/s (± 5.8 KTAS) in airspeed. This shows that all pilots tried to fulfill the task, but only pilot C accepted a higher landing approach speed.

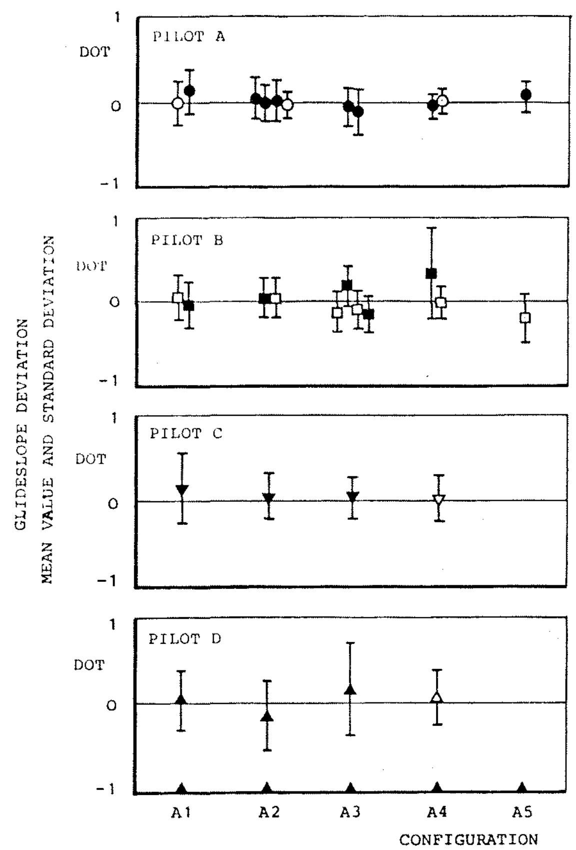

Figure 9. Glideslope tracking performance

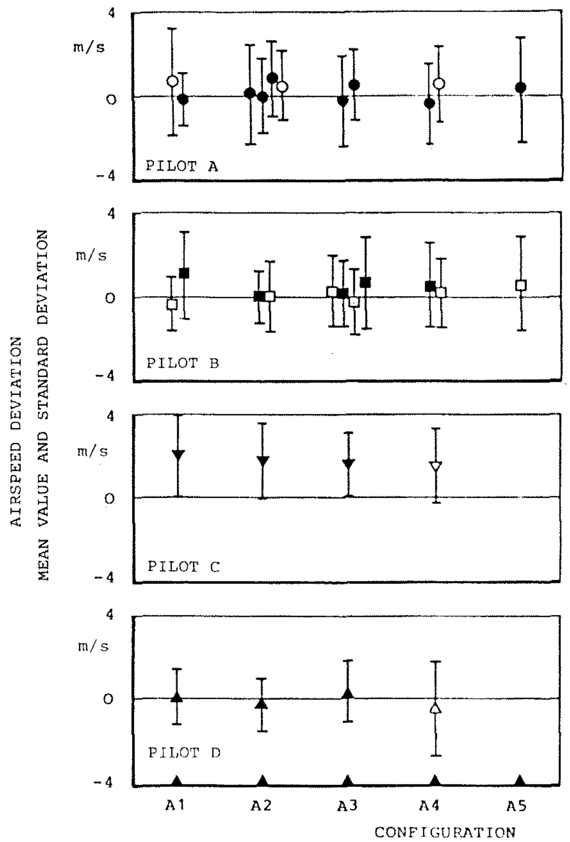

Figure 10. Airspeed tracking performance

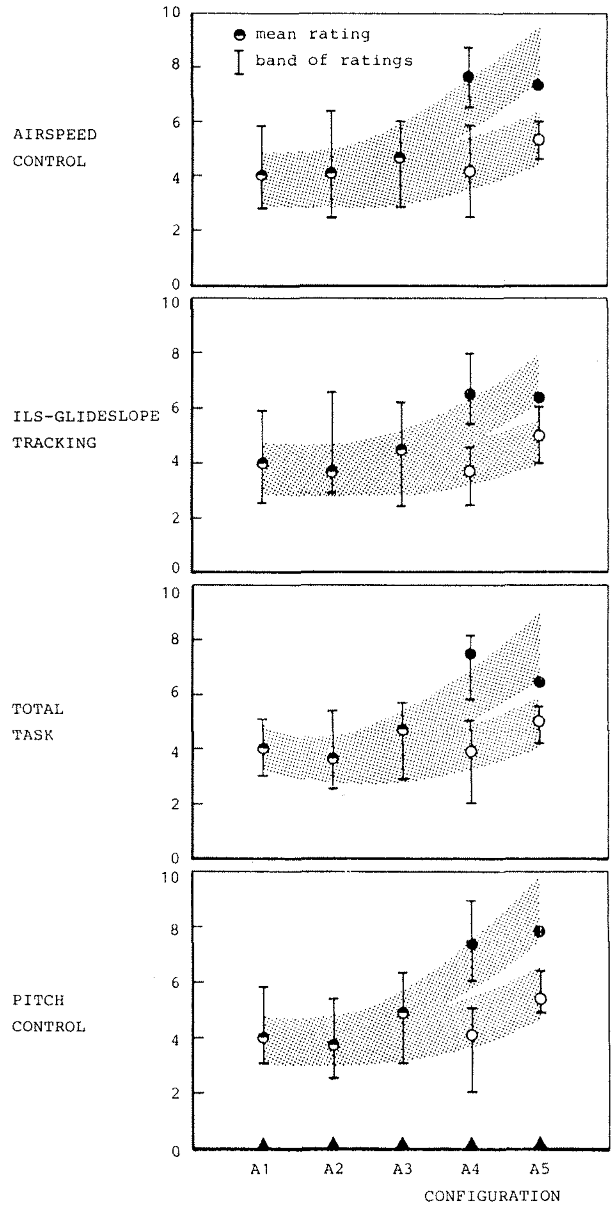

Figure 11. Pilot effort ratings

No remarkable change could be detected in pitch control activity.

The effort ratings shown in Figure 11 correlate well with the Cooper-Harper ratings in Figure 8. The effort rated by the pilots for performing the Total Task and the subtask Pitch Control decreases when changing from Configuration A1 to Configuration A2. Effort ratings for the subtasks Airspeed Control and ILS-Glideslope Tracking remain nearly constant. This confirms the overall tendency that a translation of the c.g. position from 35% MAC to 44 % MAC leads to a slight improvement in flying qualities. A further translation of c.g. position to the rear results, however, in a deterioration in flying qualities which can be identified in an increase in effort ratings for the individual subtasks combined with an increase in the overall Cooper-Harper ratings.

Influence of Pitch Control Effectiveness

The results presented in Figure 12 show a remarkable influence of pitch control effectiveness on the Cooper-Harper pilot ratings obtained. The level of unacceptable flying qualities (PR > 6.5) is reached for Configuration C2, which was flown in moderate turbulence by all pilots.

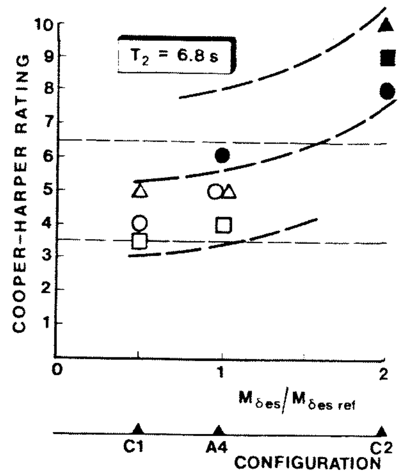

Figure 12. Cooper-Harper pilot ratings

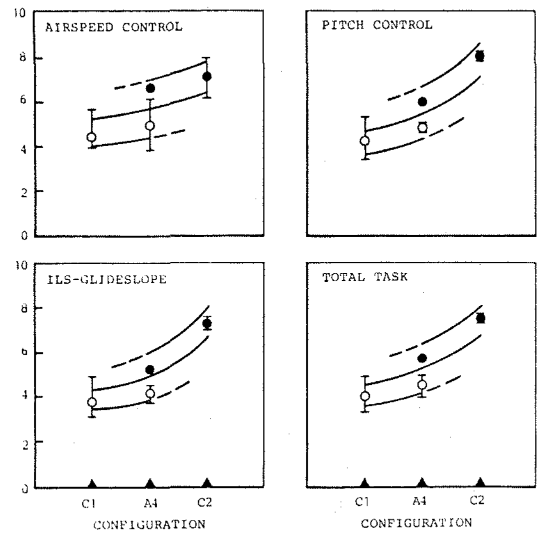

Figure 13. Pilot effort ratings
(o mean ratings I band of rats.)

Compared to the reference Configuration A4, the Configuration C2, with twice the control effectiveness, was rated worse and the aircraft Configuration C1, with half the control effectiveness of Configuration A4, was rated slightly better. Although Configuration C2 was flown in turbulence only, a deterioration in flying qualities of Conf. C2 compared to Conf. A4 probably exists in the absence of turbulence, too, as indicated by the dashed lines. The high control effectiveness configuration was characterized as "oversensitive and dangerous" by the pilots. They run into difficulties because of continuously overcontrolling the airplane (ratings of 8 and 9 on the Cooper-Harper scale). On the basis of the pilots' comments the airplane would not be flyable to touchdown in turbulence. A slight improvement in the flying qualities can be seen for the individual pilots for the low control effectiveness configuration in comparison with the reference airplane, indicating that a lower boundary where the airplane's response becomes too sluggish was not achieved in these investigations.

Figure 13 presents for each configuration both the mean values of the effort ratings of all pilots and the corresponding bands of ratings. The effort ratings shown in this figure correlate well with Cooper-Harper pilot ratings. The effort needed by the pilots to perform the total task and all subtasks increases when changing from reference configuration to Configuration C2 and decreases with the reduction in pitch control effectiveness.

Influence of Pitch Damping

In Figure 14 the Cooper-Harper ratings for Configuration B1 ($M_q = 0.5\ M_{qref}$) and Configuration B2 ($M_q = 2.0\ M_{qref}$) are presented.

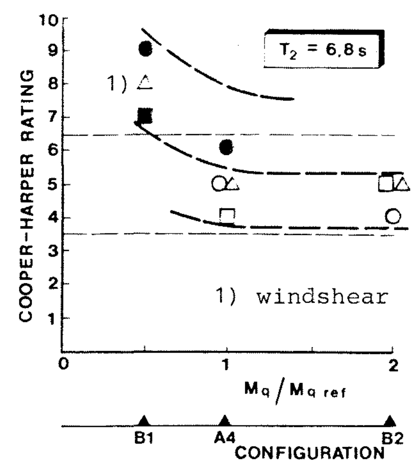

Figure 14. Cooper-Harper pilot ratings

Again one configuration (B1) was flown in moderate turbulence by all pilots. Although the turbulence intensity was only light during the mission of pilot D, the presence of windshear made the accomplishment of his task more difficult.

Changing from the reference configuration to Configuration B1 leads to a remarkable deterioration in pilot ratings. This effect is caused by both the reduction in pitch damping and the increase in turbulence intensity.

Decreasing the pitch damping in combination with a constant amount of instability (time-to-double amplitude) causes difficulties for the pilots. Configuration B1, which had half of the level of pitch damping of the reference aircraft, was extremely difficult to fly in turbulence and windshear conditions. For the pilots participating in the in-flight simulations it was not possible to acquire or to maintain a given pitch attitude.

No clear tendency in pilot ratings as a result of doubling the pitch damping is identifiable in Figure 14, if only the pilot ratings for the flights with the same turbulence conditions are considered. The pilot effort ratings presented in Figure 15 show the same tendencies as the Cooper-Harper pilot ratings. The effort needed by the pilots increases with decreasing pitch damping and remains nearly constant if the pitch damping is doubled.

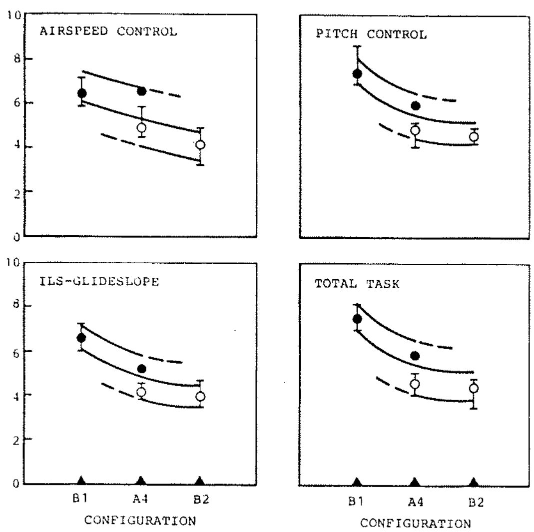

Figure 15. Pilot effort ratings (o mean rating I band of rats.)

7. <u>Comparison of results with data from similar investigations</u>

In the previous sections of this paper the influence on pilot ratings of the parameters varied in this investigation was presented. In the following the results will be compared with data from similar experiments investigating different transport aircraft configurations.

The investigation of the flying qualities of relaxed stable and unstable transport aircraft configurations was intensified in 1972, in order to investigate the low speed landing approach flying qualities of SST configurations.

The time-to-double amplitude of the aircraft's unstable response in pitch attitude or angle of attack to elevator inputs was found to be the most important parameter for the definition of minimum flying qualities. Figure 16 presents a comparison of the results given in References (4 to 6), concerning the landing approach flying qualities of SST configurations, with the DFVLR results.

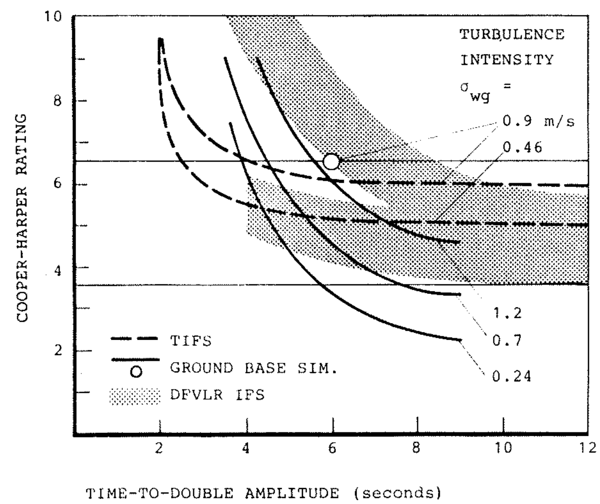

Figure 16. Comparison of results (SST landing approach)

From this comparison a similar trend in pilot rating can be identified as a function of time-to-double amplitude. All data indicate a lack of sensitivity of pilot rating with time-to-double amplitude if T_2 is greater than about 6 seconds. The Cooper-Harper ratings belonging to the SST experiments show a remarkable deterioration for times-to-double-amplitude of less than 6 seconds in one case and of less than 3 seconds in the other case. They are strongly influenced by the turbulence intensity. The results obtained from the DFVLR in-flight investigations fit the given curves well. They confirm the fact that the flying qualities of *slightly* unstable aircraft are highly affected by turbulence and are independent of time-to-double amplitude up to a certain level of instability.

Since 1977 new flying qualities investigations of transport aircraft configurations with relaxed static stability have been conducted. The most varied parameter with those experiments was the c.g. position or static margin.

Figure 17 represents the Cooper-Harper pilot ratings resulting from two simulator experiments (7,8,) investigating the influence of static margin on pilot acceptability of minimum longitudinal stability for the landing approach task and the results from the DFVLR in-flight simulation program.

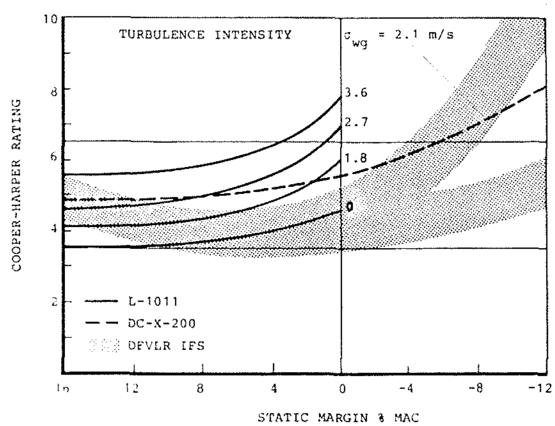

Figure 17. Comparison of results (landing approach)

The aircraft models used in the simulator investigations were the DC-X-200 and the L-1011; the Lockheed investigations did not consider unstable configurations. In general the DFVLR results fit the given curves well; however, they show a drop in pilot ratings for small values of static margin, i.e. near the stability boundary the aircraft configurations investigated in-flight by DFVLR are rated better than the L-1011 configurations. For greater negative values of static margin (i.e. for higher levels of instability) the pilot ratings obtained from the DFVLR flight tests performed in moderate turbulence are worse than the ratings given for the DC-X-200 configuration investigated under comparable turbulence conditions.

8. Conclusions

The DFVLR in-flight simulator was used to investigate the influence of stability reduction on the landing approach flying qualities of transport aircraft. In this flight test program the static margin was varied from 14 % MAC to -10 % MAC by rearward center of gravity translation. In addition the values of pitch damping and pitch control effectiveness were changed in combination with a constant amount of instability.

The pilot ratings and comment data obtained in this experiment suggest the following conclusions:

Influence of C.G. Position

- No clear tendency of Cooper-Harper pilot ratings to deteriorate with decreasing stability is detectable until inherent instability, corresponding to 6 seconds time-to-double amplitude, is reached.
- Cooper-Harper ratings for all pilots show a slight improvement when the static margin is changed from 14 % to 5 % MAC.
- Pilot ratings deteriorate for configurations with a time-to-double amplitude of their unstable motion of less than 6 seconds.
- The effect of turbulence on the pilot ratings is relatively low until time-to-double amplitude reaches about 6 seconds. For configurations with a time-to-double amplitude of less than this value, however, the influence of turbulence becomes greater and the intensity determines the gradient of deterioration.
- Both pilot effort ratings and comments confirm the Cooper-Harper rating tendency. After an initial drop their effort to fulfill the task with the same accuracy in all cases increases with increasing instability.
- Compared with the results of former investigations concerning the landing approach flying qualities of relaxed stable transport aircraft configurations, the results of the DFVLR in-flight experiments show a similar trend in pilot rating as a function of time-to-double amplitude or static margin.

Influence of Pitch Damping and Pitch Control Effectiveness

- The flying qualities of the evaluated aircraft configurations are highly affected by both parameters, pitch damping and pitch control effectiveness.
- Decreasing the pitch damping in combination with an unchanged amount of instability leads to unacceptable flying qualities due to extreme difficulties with pitch attitude tracking.
- High values of pitch control effectiveness tend to make the aircraft to become oversensitive, and are not accepted by the pilots.
- The pilot ratings are influenced by the encountered turbulence.

9. References

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Appendix 1

Configuration	A1	A2	A3	A4 *)	A5	B1	B2
CG location (% MAC) static margin (% MAC)	35 14	44 5	49 ≈0	55 -6	59 -10	-	-
$C_{m\alpha}$	-0.923	-0.410	-0.124	0.218	0.440	0.100	0.440
short period root							
ω_{nsp} (1/s)	0.75	0.60	-	-	-	-	-
ζ_{sp}	0.77	0.92					
$T_{1/2}$ (s)	1.20	1.25					
phugoid root							
ω_{np} (1/s)	0.15	0.11	-	-	-	-	-
ζ_p	0.03	0.17					
$T_{1/2}$ (s)	147.5	36.20					
new oscillatory root	-	-					
ω_n (1/s)			0.18	0.24	0.25	0.22	0.26
ζ			0.99	0.57	0.47	0.51	0.65
$T_{1/2}$ (s)			3.78	5.01	5.96	6.20	4.08
aperiodic roots	-	-					
time constant τ_1 (s)			1.28	1.04	0.96	1.265	0.75
$T_{1/2}$ (s)			0.89	0.72	0.66	0.88	0.52
time constant τ_2 (s)			-457.6	-9.75	-6.88	-9.91	-9.77
T_2 (s)			317.1	6.76	4.77	6.87	6.77

*) Same values belong to Configurations C1 and C2

Table 2. Characteristics of selected configurations